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13. ABSTRACT (Maximum 200 Words)

The Spacewatch Project discovered comets and Trans-Neptunian, Centaur, Trojan, Main-Belt, and Earth-approaching (EA) asteroids, providing information about the evolution of these objects and their orbits. Spacewatch also found asteroids that might present a hazard of impact on the Earth, and recovered high-priority comets and asteroids that were too faint for most other asteroid observing stations.

During this grant interval, Spacewatch made a total of 3,885 positional measurements of 440 EAs, 96 of which were new Spacewatch discoveries. The statistics of Spacewatch's detections of EAs permitted new estimates of the total number of EAs larger than 1 kilometer in diameter and of the number of Potentially Hazardous Asteroids (PHAs).

The 1.8 meter Spacewatch telescope became operational during this report period. With it, Spacewatch contributed more observations of faint PHAs than all other observing stations combined.

A mosaic of CCD detectors was installed on the Spacewatch 0.9-meter telescope during this grant period. It covers in each lunation an average of 1500 square degrees. Twelve EAs and two comets were discovered with this system in the first 3 months of operation with it.

Progress was made toward establishing the capability for astrometry of asteroids at observatories in Mongolia and NW Australia.

Spacewatch: <http://spacewatch.lpl.arizona.edu>.

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**FINAL REPORT for GRANT
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University of Arizona
Steward Observatory
from the
U. S. Air Force Office of Scientific Research**

Title: **Spacewatch Survey for Asteroids and Comets**

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Principal Investigator: **Robert S. McMillan** Date 15 July 2003

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Summary

The goals of the Spacewatch Project are to discover small bodies in the solar system and to analyze the distributions of their orbits and absolute magnitudes. Astrometric imaging observations are conducted on an average of 3 weeks per month with the 0.9-meter and 1.8-meter Spacewatch Telescopes on Kitt Peak mountain in the Tohono O'odham Nation, Arizona. Our discoveries support studies of the Trans-Neptunian, Centaur, Trojan, Main-Belt, and Earth-approaching (EA) asteroid populations. These studies provide information about the evolution of these objects and their orbits. Spacewatch also finds potential targets for space missions, finds objects that might present a hazard of impact on the Earth, provides accurate astrometry of tens of thousands of asteroids annually, and recovers and does astrometry of high-priority comets and asteroids that are too faint for most other asteroid observing stations.

During this grant interval, we made a total of 3,885 positional measurements (1,142 detections) of 440 EAs, 96 of which were new Spacewatch discoveries. We observed the other EAs to improve their orbits. Spacewatch also discovered 6 Centaurs or Scattered Disk Objects, 3 Trans-Neptunian Objects (TNOs), and 9 comets during this report interval. Statistics of Spacewatch's detections of EAs permitted new estimates of the total number of EAs larger than 1 kilometer in diameter and of the number of Potentially Hazardous Asteroids (PHAs).

The 1.8-meter Spacewatch telescope became operational during this report period and is the largest telescope in the world dedicated exclusively to discovery and astrometry of comets and asteroids. It has a limiting magnitude of $V=23.3$, 4 mags fainter than the LINEAR survey (Stokes *et al.* 2000). With this telescope, Spacewatch contributes more observations of faint PHAs than all other observing stations combined. Thus Spacewatch's fainter magnitude limits and sensitivity to slower motions permit comprehensive discovery and followup of EAs at relatively large distances from Earth, thereby helping to complete the survey for hazardous asteroids.

A mosaic of CCD detectors for the Spacewatch 0.9-meter telescope was funded by NASA and installed on the telescope during this grant period. As the latest significant entrant into the search for EAs, the new mosaic of CCDs on the 0.9-m telescope now covers in each lunation an average of 1500 square degrees of the most important regions of the sky for EA discovery. Twelve EAs and two comets were discovered with this system in the first 3 months of operation with it.

Progress was made toward establishing the capability for astrometry of asteroids at observatories in Mongolia and NW Australia.

Spacewatch is described at the URL <http://spacewatch.lpl.arizona.edu>.

CONTRACTUAL MATTERS

This grant covered about one fifth of Spacewatch's salary and operating expenses during this report interval. The original termination date of this grant was 31 October 2002, which would have dictated a final report by Jan. 31, 2003. However, in order to complete an additional task requested by Major Bellaire of AFOSR, we requested and received a No-Cost Extension to 30 April 2003. We therefore replaced the final report of 30 Jan. with a progress report at that time, and are sending this final report now. The AFOSR continued funding Spacewatch with grant F49620-03-0107 which began on 1 December 2002.

ACTIVITY REPORT

Discoveries: During this report period, Spacewatch discovered 96 EAs. That total includes 16 Potentially Hazardous Asteroids (PHAs) with $H \leq 22$, 2 PHAs with $H \leq 18$, and numerous objects that appear or have appeared in the past on the NASA JPL risk web site. Spacewatch also discovered 6 Centaurs or scattered-disk objects, 9 comets, a satellite of Jupiter, and 3 Trans-Neptunian Objects (TNOs) during the report period. Consistent with expectations soon after it went into operation, the new mosaic of CCDs discovered the large ($H=17.9$) Apollo PHA 2003 KU₂ in an orbit of high eccentricity, as well as one other highly eccentric PHA, 10 other EAs, and two comets. At a discovery V magnitude of 20.7 and an angular rate of 0.4 deg/day, 2003 KU₂ is typical of the less accessible objects that need to be found to complete the inventory of the large EAs.

Followup Astrometry: During the report period, Spacewatch observed and reported 3,885 positions of 440 EAs (including 147 PHAs with $H \leq 22$), 434 positions of comets, and recovered one comet. Within the last two years, Spacewatch contributed more than six times as many observations as the next most productive station and more than all other stations combined.

Incidental Astrometry (IA): During the report period, Spacewatch sent 336,991 astrometric detections of asteroids to the MPC. (One "detection" by Spacewatch usually equals three observations of position.) This total includes results from both telescopes but not the results of reprocessing our data archive from 1990-1999, which is listed separately below. Provisional designations for 21,700 asteroids resulting from those observations during this report period have been credited by the MPC to Spacewatch. Most of those are in the main belt, but a few examples of incidental precoveries of interesting objects extracted by the MPC from our IA include 2001 WG₂ (an Apollo of high eccentricity and inclination), 2001 XN₂₅₄ (a PHA with $H=17.5$), periodic comet P/2002 BV, Mars crosser 2002 YK₂₉, and Amor 2003 HB₆.

Usage of the 1.8-m Telescope: Routine operation of the telescope by solo observers began on 2001 October 16 and improvements to the efficiency of its operation are continuing. This telescope is dedicated to surveying and followup in about equal proportions, with an emphasis on PHAs. The first EAs discovered with the Spacewatch 1.8-m telescope were 2001 UO and 2001 UB₅ on 2001 October 16 and 18, respectively. The unusually faint PHA 2001 SB₁₇₀ was

recovered with the 1.8-m telescope on 2001 Oct. 13 at V magnitude 23.3 at the urgent request of the Spaceguard Central Node in Italy, resulting in the elimination of some predictions of future collisions of this object with the Earth. About 1,692 positional measurements (530 detections) of 255 EAs have been made with the 1.8-m telescope, including 28 EAs discovered with the 1.8-m telescope. On 2003 June 18 the 1.8-m primary mirror was realuminized for the first time in 4 years. In early July 2003 the cooling system of the CCD was boosted with greater heat pumping capacity to deal with the hot summers here.

The Number of Large Earth-Approaching Asteroids: Using Jedicke *et al.*'s (2002) technique to debias Spacewatch detections of EAs, Bottke *et al.* (2002) estimated that the total number of EAs with $H \leq 18$ is 960 ± 120 . This is consistent with the estimate of 700 ± 230 made by Rabinowitz *et al.* (2000) from JPL/NEAT observations and less than 2σ from the 1227 (+170, -90) determined by Stuart (2001) from detections by LINEAR. Bottke *et al.*'s (2000, 2002) model is more rigorous than earlier studies, is the first to distinguish between the orbital properties of the discovered and undiscovered EAs, and predicts that most of the undiscovered EAs have more extreme values of a , e , and i . Jedicke *et al.* (2003) show that this model can be used with knowledge of the evolving capabilities of the search programs to predict when the goal to discover 90% of the EAs larger than 1 km in diameter will be reached. At the present rate of surveying by all groups, Jedicke *et al.* (2003) predicted that this milestone may not occur until 2025, although subsequent to their paper, those authors revised their estimate to 2014.

Potentially Hazardous Asteroids: Detections of EAs by Spacewatch have made possible an estimate of the number of PHAs. The MPC's definition of a PHA is any asteroid with at least one orbital node between 0.95 and 1.05 AU from the Sun and absolute magnitude $H \leq 22$. The modeling of the evolution of asteroids into EAs by Bottke *et al.* (2002) and the determinations of observational bias and efficiency by Jedicke provide estimates of the number of PHAs and the distribution of their orbits. One of the relevant parameters is the MOID: Minimum Orbital Intersection Distance, with reference to the orbits of the asteroid and the Earth. Approximately 21% of the EAs with $H \leq 18$ in their model have $\text{MOID} < 0.05$ AU, 1% have MOIDs less than the distance to the moon, and 0.025% of them have MOIDs less than an Earth radius. Since there are roughly 1000 EAs in the current population with $H \leq 18$, this implies that there are about 200 PHAs with $H \leq 18$ (there are 109 known now) and likely only ten such objects with MOIDs less than the distance to the Moon. There is a 25% chance that at least one EA with $H \leq 18$ would have a MOID less than an Earth radius. That, of course, does not mean that there is a 25% chance of such an asteroid hitting the Earth, because the MOID does not take into account the positions of the asteroid and the Earth in their orbits.

Number of EAs with Diameters ≥ 1 km: Another collaboration including Jedicke (Morbidelli *et al.* 2002), using Spacewatch data and a new estimate of the average albedo of EAs, estimated that the number of EAs with diameters ≥ 1 km is 855 ± 110 . That is somewhat less than the number of EAs with $H \leq 18$ because Morbidelli *et al.*'s higher estimate of the average albedo corresponds to slightly smaller asteroids at any given absolute magnitude H .

Outer Solar System: Because of our relatively large field of view and our bright limiting magnitudes compared to other surveys of the outer solar system, the primary contribution of Spacewatch is in the discovery of the rarer, larger objects. Larsen *et al.* (2001) reanalyzed 1,484 square degrees of archived scans to a magnitude limit of $V=21.8$ using special software that Larsen developed for sensitivity to smaller angular displacements of images of objects. They discovered 5 new Centaurs/Scattered Disk Objects (out of a total of 7 detected by them) and 5 TNOs (out of a total of 9 detected by them) in this manner. After debiasing for observational selection effects, they determined the bright ends of the cumulative luminosity functions (CLFs) of Centaurs and TNOs, extending 0.7 mag brightward for TNOs and 3.5 mag brightward for Centaurs on the cumulative density surface plots, into regions previously described only in terms of limits. The CLF of the Centaurs seems to have the same power law as that of the TNOs. Extrapolation suggests that there should be 100 Centaurs, 400 TNOs, and 70 Scattered Disk Objects brighter than $R=21.5$.

Mosaic of CCDs:

To increase the area covered by the 0.9-m telescope, we paved its focal plane with a mosaic of four CCDs. This major upgrade was funded by NASA. The mosaic was installed on the 0.9-m Spacewatch Telescope, rather than the 1.8-m, for practical reasons. The pixels of the CCD are 13.5 microns square, so an effective focal length of 2.8 meters is required for the image scale of 1 arcsec per pixel (to which our software is tuned and which is required to reach our limiting magnitude). This focal length was achieved more readily with the smaller of our two telescopes because on the 0.9-m telescope it did not produce too fast an f /number for the large lenses needed to correct and flatten the field of view. Our URL <http://spacewatch.lpl.arizona.edu/09meter.html> illustrates the change in the optical configuration of the telescope. The mosaic of four edge-butable CCDs covers a solid angle of 2.9 square degrees, about nine times larger than our previous CCD. The URL shows the layout of the four CCDs in the new focal plane, compared with the size of our old CCD projected onto the same image scale. To cover sky faster than the sidereal drift rate, observations with the mosaic are made in the “staring” mode. The observing cycle goes as follows. We expose for 120 sec on each sky field. Each 120 sec exposure is followed by a 75 sec readout of the CCDs and 45 sec to slew and settle the telescope and dome to the next field, making a 240 sec cycle per exposure. It takes 40 minutes to cycle once through ten such pointings. We return to each of the ten pointing centers in a “region” three times over 120 minutes. Thereby we search the sky with the mosaic of CCDs to the same limiting magnitude as before ($V=21.7$), but about six times faster and with a time baseline of 80 minutes for detecting motion.

First light on the new optics of the Spacewatch 0.9-meter telescope was achieved on 2002 October 10 and first light on the complete system with the mosaic of detectors occurred on October 22. The first detection of an EA, the Potentially Hazardous Asteroid 2002 TD₆₆, was made with the mosaic on Oct. 23. Regularly scheduled observing with the mosaic began on 2002 Oct. 28 and all-night observing with the mosaic began on Nov. 4. The first discoveries of new asteroids with the mosaic were made and sent to the MPC on 2002 Nov. 6. During this first

observing run, none of the automated scripts for observing procedures had been installed yet, but even with some system latencies and the solo observer having to command every action, the rate of coverage of sky area had already reached six times that of our old system on that telescope.

After some additional engineering to reduce CCD read noise, survey-grade observations began on 2003 March 8. As of 2003 June 16, the mosaic system had been operated in survey mode on the Spacewatch 0.9-meter telescope for 47 nights, yielding 62,257 detections of asteroids. Of those detections, 59 were incidental (non-targeted) detections of EAs. Twenty of those 59 were EAs with $H \leq 18$, and 13 of them were new discoveries of EAs of all sizes. A total of 4,263 square degrees were surveyed in those 47 nights, in which revisits of given areas were counted as new if they occurred more than 5 days apart. For comparison, during the interval from Jan. 2000 to April 2002, the 0.9-m telescope with the old 2Kx2K CCD discovered 53 EAs and rediscovered another 42 EAs for a total of 95 detections during 29 lunations or an average of 3.3 EA detections per lunation, not counting deliberately targeted EAs. However, in the first three lunations with the mosaic, we made 13 discoveries and 46 rediscoveries for an average of 19.7 detections per lunation or an increase of six times. Table 1 summarizes the Minor Planet Electronic Circulars (MPECs) resulting from operations with the Spacewatch CCD mosaic to date.

Table 1. Minor Planet Electronic Circulars resulting from observations with Spacewatch CCD Mosaic since routine observing began on 2003 Mar. 8, in chronological order.

MPEC	Object	Type	H	Obs. Type	Vmag	Comment
2003-E38	2003 EN16	Amor	18.7	Discovery	20.4	$a=1.68, e=0.36, i=18.3$
2003-E41	2003 EZ16	Amor	22.7	Discovery	20.4	Not planet crossing
2003-F57	2003 FQ6	Amor	21.1	Discovery	21.0	Low e,i
2003-F58	2003 FR6	Amor	19.9	Discovery	19.4	High e,i
2003-G38	2003 GJ21	Amor	23.1	Discovery	20.2	High e
2003-G44	2003 GS22	Amor	23.0	Discovery	21.6	High a,e
2003-H36	2003 HB6	Amor	17.8	Precovery	19.8	High a,e
2003-J05	2003 HU42	Amor	18.6	Discovery	21.5	
2003-J21	2003 JG4	Amor	23.1	Discovery	21.4	High e
2003-J35	2003 JC11	MC	18.6	Discovery	21.0	High a,e,i
2003-J41	2003 JC13	Apollo	20.6	Discovery	19.8	PHA; low a
2003-J45	2003 JF13	MC	21.0	Discovery	21.6	High e
2003-J52	2003 JV14	Apollo	21.1	Discovery	19.4	High e
2003-K14	C/2002 U2	Comet		IA Obs.	20.0T	Comet LINEAR
2003-K26	2003 KU2	Apollo	17.9	Discovery	20.7	PHA; high e
2003-K34	P/2003 H4	Comet		IA Obs.	17.8T	Comet LINEAR
2003-K37	C/2003 K1	Comet		Discovery	20.2N	Comet Spacewatch
2003-K54	2003 KN18	Apollo	19.1	Discovery	20.8	PHA; High e
2003-L11	2003 KK20	Hungaria	17.9	Discovery	22.0	$a=3.02, e=0.24, i=42$

2003-L30	0053P	Comet	IA Obs.	14.7T	
2003-L33	C/2003 L1	Comet	Discovery	19.7T	Comet Scotti

Asteroid Astrometry in Mongolia:

This grant included funds to help develop the capability of asteroid astrometry in Mongolia. This was stimulated by initial contacts between USAF personnel and the astronomers there, and is justified by their location. A large percentage of their nights are clear, their climate is dry, and their weather mostly uncorrelated with that at other observatories. Observations of recently discovered rapidly-moving EAs made from the longitude of Mongolia will provide especially valuable updates to the knowledge of their orbits because there are few astrometric observatories in that range of longitudes. Some of the very nearby objects discovered by Spacewatch are especially in need of rapid response because they are moving so fast. The relatively high latitude of Mongolia is not too much of a handicap because the Dominion Astrophysical Observatory near Victoria, British Columbia, Canada is at a similar latitude and has done a great deal of astrometry of faint EAs discovered by Spacewatch - and their climate is much worse for astronomy than the climate in Mongolia. Furthermore, the Siding Spring Observatory in Australia is now back on line doing followup on EAs, and their southern latitude allows them to observe those EAs that are too far south for observation from Ulaanbaatar.

We procured and sent to our Mongolian colleagues a brand new Meade 16-inch (0.4-m) LX-200 "GOTO" telescope (fully computer controllable and scriptable), an SBIG ST-6 computer-controlled thermoelectrically cooled CCD camera, two computers, and all the required software, interfaces, cables, and accessories. These were all purchased with funds from our AFOSR grant. This system required some debugging and upgrading by our staff before it was suitable for use. Mr. T. Bayaraa had a very successful period of training in asteroid astrometry with the new equipment in Tucson. He learned how to connect all the cables, start all the software, initialize and refine the telescope pointing, and take and display images with the CCD detector. He also demonstrated proficiency in determining what asteroids need to be observed, running ephemerides of them, finding them with the telescope, doing astrometry with the CCD images containing asteroids, identifying the asteroids as moving images, and preparing astrometric reports for mailing to the MPC. He passed several tests that our observers gave him, such as noticing when an obscure cable was deliberately omitted from the system, and has learned how to recover from other anomalies, both accidental and those deliberately introduced by his trainers. He also observed with the telescope, both solo and in the presence of witnesses, and produced acceptable observations.

We encouraged Dr. Bekhtur to allow Bayaraa to transfer his accumulated knowledge to the other observers and technicians at the Ulaan Baatar Observatory as soon as possible, and to stimulate their interest in asteroid research. In the meantime, we are very pleased that he absorbed all the training that a number of Spacewatch observers and engineers have prepared for him. He has thus become a valuable investment toward the success of our mutual project, and we hope that he

will continue to be a key person in their operation.

In Mongolia the telescope was subsequently mounted in their new roll-off roof observatory, the polar axis was aligned, and internet access to the observatory was acquired. Additional Mongolian observers were apparently trained by Bayaraa and are observing and reporting astrometry of asteroids. We have exchanged email messages on the topic of some software glitches that have arisen since the time the system was shipped to Mongolia. The Spacewatch staff remain available for consultation via email and FAX at all times, and we hope that our Mongolian colleagues will notify us promptly of any further difficulties they encounter.

The salaries and wages for nine people part-time from September 2000 through April 2001, employee-related expenses, indirect costs, telescope, pier, camera, Sky Tent, extra pier and supplies to set it up, a small amount of machine shop time to modify the telescope, crates and shipping, Internet access for the temporary training setup in Tucson, twin Mongolian computers, software, rental of a jack hammer and pallet jack, supplies, Bayaraa's airfare and per diem cost more than half of our FY 2001 grant from AFOSR. However, if those expenses are averaged over the three year grant period (1999-2002), the cost is not much greater than we estimated in our original proposal.

In 2002 we exchanged some emails with our Mongolian colleagues to help them set the parameters of the commercial astrometry software they are using. They report that their astrometric results are now "more or less correct". On 13 August 2002 we were told that the telescope and CCD provided to them by this grant were operational. They reported having observed on 95 nights and having taken 2339 images of 456 objects, 381 of which were asteroids and 75 were EAs. Their limiting V magnitude is 18.5, typical for that detector and aperture of telescope. The effect of low ambient temperatures in the winter on the declination bearings of the telescope is a continuing problem.

They sent us a copy of their observations for our evaluation. Their selection of asteroid targets is good and the observations seem to be well executed. We compared the astrometric positions they reported with the expected positions of those asteroids computed from their known orbits and made some conclusions and recommendations.

Most of the observations agree with the computed ephemerides within the expected tolerances and the internal scatter of their observations is what one would expect for that equipment. That is adequate for followup observations of EAs. In about 25% of the cases, however, the recorded times of the observations, and the residuals, indicate erroneous setting of the computer clock. In some cases the clock was set to local zone time instead of Universal Time (UT). In some other cases there appears to have been an error with AM/PM of the time of day (resulting in an error of 12 hours), and in yet other cases the clock may have been simply incorrect. We urged them to remind their observers to check the computer clock every evening against a radio broadcast or telephone or internet broadcast of time.

In a couple of cases the packed designations of asteroids were made incorrectly. Those must be expressed as "J97X11F", for example, and not "1997XF11". That is important for the MPC to be able to process the data. Finally, we encouraged them to observe the same asteroids on multiple nights. It is important to get at least 2 nights on each asteroid for positive identification and for the MPC to issue recovery credit. Observations of the same objects on three separate nights would be even better. With these minor corrections in procedure, we think it will soon be possible for the Mongolians to send a batch of observations to the MPC.

Asteroid Astrometry in Northwest Australia:

On 28 Sept. 2001, the Program Manager of our grant, Maj. Paul Bellaire, asked us to order equipment for astronomer John A. Kennewell at the Learmonth Solar Observatory near Exmouth in Northwestern Australia to do followup astrometry of bright EAs and measure lightcurves of selected asteroids. This service is in addition to the original goals of this grant, so additional funds were awarded for it.

An additional astrometric station in the southern hemisphere will help refine the orbital parameters of asteroids that move south after discovery. This telescope will also survey the southern hemisphere sky for EAs and other asteroids. The site has a dry climate and clear skies for 80% of the year. The telescope will provide a monitor of EAs in the southern sky to better than magnitude 18. Rotational photometry at the Learmonth site will investigate spin rates and principal axes of EAs. These are physical characteristics that are vital for the applied mitigation phase of planetary defense.

A complete 14-inch (0.36-meter) telescope system, CCD imaging detector, and software, were subsequently ordered by us to be delivered directly to Dr. Kennewell. Due to delays in taking delivery of the equipment, we were compelled to request an extension of this grant to 30 April 2003. All hardware with the exception of two minor items has been received and is on site at Learmonth. Power has been connected to the observatory dome, and network and other data cables are in place. The computer system has been set up, both in the dome and in a remote building (where most data analysis will occur). The pier was remachined because it would not accept the Paramount robotic mount. Installations of the mount and of the telescope on the pier are expected in the next few weeks, and first light by the end of August. Work is also in progress on a web site for the project. Kennewell had expected to be a little further along by now, but a request from the USAF Weather Agency necessitated the development of a new solar image processing system, to replace a system that is no longer maintainable.

Kennewell's current observational plan remains as per the original proposal. He expects to operate a minimum of 5 nights per lunation. Initially at least, 70% of the observations will be devoted to follow-up positional determination, 30% to searching regions of the sky not readily accessible to northern telescopes (ie outside Spaceguard guidelines), with the possibility of a small amount of time devoted to light curve determinations (asteroid rotation analysis).

(Kennewell is currently assisting Sydney University with light curve determinations of eruptive variables.)

Automation of a Spacewatch Telescope:

NASA provided funds to automate one of the two Spacewatch telescopes. This report covers the work from late August 2002 when the funds arrived through 7 July 2003.

Before choosing which telescope to automate, we proposed to make both telescope facilities more reliable. There have always been hazards and minor recurring anomalies, mostly in mechanical systems, that are simple for a human operator on-site to avoid or correct, but must be eliminated before a computer can control everything.

General system conceptualization and planning has been extensive but will not be detailed here. One highlight is that we think using digital signal processors (DSPs) for process controllers and for a watchdog or overlord provides the advantages of communication versatility, friendliness of programming, and fast rebooting.

Progress at the 0.9-meter Spacewatch Telescope:

We have revised the telescope control software for more commonality with that at the 1.8-meter telescope.

We have built a dome azimuth encoder system, interfaced it into the telescope control computer, programmed the computer to display the azimuths of the telescope, dome, and their difference, and put it into service. This is a major breakthrough at this old observatory, allowing the observer to turn the dome safely from the control room while slewing the telescope over small angles. It has been in use without failures or anomalies since mid-February 2003 and has improved observing efficiency and reduced observer fatigue.

Four video cameras were mounted on the 0.9-m telescope to provide the observer in the control room an unambiguous view of the dome shutter opening as seen from the telescope, regardless of telescope pointing angle. Although this does not aid automation *per se*, it allows remote control of the telescope and dome, a necessary intermediate step toward automation.

We designed and procured some of the hardware for a new dome rotation system that will replace the two old motors that have been cycled on and off for 41 years. New motors, right angle drives, and variable frequency drive controllers will accommodate computer- as well as manual control.

The 41-year-old dome shutter chain and drive was serviced to prevent its catching while opening and closing.

We investigated the cause of a recurrent oscillation of the telescope about the declination axis during slews, suppression of which required a human operator. It was caused partly by a mismatch of inertias of the load (telescope) and the rotor (motor and shaft driving the worm and wheel). The problem has been reduced by adding an inertia wheel on the motor side of the worm, thereby increasing the moment of the rotor end. Adding a harmonic gear box should eliminate the remaining bounce and will allow super fine resolution for tuning acceleration and deceleration rates better.

We worked toward integrating the computer that controls the telescope with that which operates the CCD detector. This will allow telescope slews, dome rotations, and CCD shutter openings and closings to be coordinated automatically. We made progress toward converting the protocol of communication with the motion control cards from PCI bus to 10 BaseT, converting the software from C into Java applets that are better suited to interprocess communication, and changing the operating system of the telescope control computer from MS/DOS to Linux.

An automated, web-accessible weather station was procured and put into service at the 0.9-m telescope. This will allow decisions to open or close the dome to be made automatically, at least in principle. In practice we will probably not allow a computer to open the dome but will allow it to close it based on environmental conditions.

Progress at the 1.8 meter Spacewatch Telescope:

We determined that the 1.8 meter dome rotation motors and mounts need to be made stronger and made compatible with encoded motion. Three phase AC power has to be added at the 1.8-m to support the variable frequency drives required for computer control of the dome position.

Absolute encoders (Linear variable differential transducers; LVDTs) for focus, tip, & tilt were installed for more reliable knowledge of the positions of these mechanical systems.

Auxiliary non-slipping encoders for azimuth & elevation were installed for more accurate knowledge and control of telescope pointing and tracking.

Data Archiving and Reprocessing:

With support from a grant from NASA/AISRP to Larsen, all 1.5 terabytes of data previously stored on magnetic tape between 1990 and 1999 were copied to DVD-RAM media. This stabilized the data and simplified reprocessing. The data covered 75,000 square degrees to a limiting V magnitude of ~ 21.5 . All of those data were reprocessed with Larsen's newest generation of asteroid detection software to yield 190,830 detections of moving objects that were undetected by the pre-Larsen software, making a total of 423,220 detections of asteroids by Spacewatch from 1990 to 1999 inclusive. (One "detection" usually equals three positions.) Thus the reprocessing yielded a 82% percent improvement on Spacewatch's effort over almost 9 years, equivalent to 7 additional years of Spacewatch operations at the level of performance at that time.

The newly derived positions have been submitted to the MPC. One immediate result was that the virtual impactor 1994 UG was retired from the JPL impact risk page. The MPC has linked 55,852 of our new archival detections with known asteroids and will continue to try to identify our detections and use them to extend the arcs of asteroids. Among the positions derived from the reprocessing, we reported 597 previously undetected asteroids with high probabilities of being EAs. The MPC has so far linked 237 of those objects with known asteroids and 66 of them have been identified with known EAs. Out of those 66 EAs, 21 are PHAs. The remaining 360 EA candidates in our reprocessing output that are as yet unlinked with known objects cannot be recovered at the telescope solely on the basis of such old data. However, our data will provide immediate information (precoveries) to the arcs of new discoveries that are identified with our earlier observations.

Database: The Spacewatch database of observed regions and objects has been created. We have developed a streamlined interface for displaying our pointing history and added the capability of doing ephemeris-based searches. The utility of this is plain to those who compute orbits -- should they find a virtual impactor or other object of interest, they can request a search of our pointing history to see whether that object may exist undetected on our images. At that point, we can be alerted to do a visual search or share data. The utility of this sharing extends beyond asteroids -- our temporal sampling may make subsets of the data interesting to astronomers in general. Without the expense of placing our imagery online, we have created a way for people to find out what data are available.

Orbit Linkage Software: The effectiveness of Spacewatch's deep limiting magnitude for finding new EAs depends on detecting the objects while they are far from Earth, typically at their aphelia. However, it can be difficult to recognize them as EAs at those times, because their angular rates may not distinguish them clearly from main belt asteroids. Such candidates might only appear in the incidental astrometry (IA) that we send to the MPC daily, and not as fast moving EA candidates specifically designated by the observer at the time of first detection. They may only be recognized after we revisit the same region of the sky two or three times within one lunation (observing run). However, the MPC does not have time to check the IA of the big surveys for such linkages promptly enough for targeted followup. Therefore, we developed our own orbit linking software that we will operate on the IA resulting from our revisits to our regions. We are testing its efficiency at identifying objects observed during a single lunation on three or more widely-spaced nights, and working to maximize the number of reliable linkages and minimize false positives. Initial runs on simulated data and real scans taken with the old 2Kx2K CCD on the 0.9-m telescope some years ago have been successful. We have selected contiguous blocks of scan regions stacked in declination (super-regions) that were visited three times within a single lunation for further tests.

Miscellaneous Distinctions:

Detection of Remnants of the Lost CONTOUR spacecraft: COMet Nucleus TOUR (CONTOUR) was to be a mission to two comets. On 2002 Aug 15, Spacewatch received an urgent request from CONTOUR mission control at Johns Hopkins University's Applied Physics Laboratory, asking for an optical detection of the location of the CONTOUR spacecraft, because radio contact with it had been lost following a commanded velocity impulse. Two exposures were made by J. V. Scotti, separated by 22 minutes of time. The trailed images of two fragments of the CONTOUR spacecraft were discovered in those exposures by J. A. Larsen. At that time, the spacecraft was 460,000 km from Earth and the two objects were separated by 460 km in the plane of the sky. This indicates that the fragments probably separated at the end of the solid rocket motor burn, 20 hours earlier, with a relative velocity of at least 6 m s^{-1} . A third fragment was subsequently found in those images by A. S. Descour. As a result of the knowledge that the spacecraft had fragmented, NASA subsequently abandoned attempts to communicate with it (http://www.space.com/missionlaunches/contour_final_021220.html) and concluded that design defects doomed it (http://www.space.com/missionlaunches/contour_design_030212.html).

Spacecraft Mission Target: The European Space Agency's SIMONE mission is targeted to Apollo asteroid 1994 CN₂ that was discovered by Spacewatch. At absolute magnitude $H=16.8$, it is the brightest of the six targets for that mission. See <http://www.esa.int/gsp/completed/neo/simone.html>.

Student Training and Employment: Spacewatch continues to be an excellent training ground for undergraduate students interested in astronomy, planetary science, electronics, or computer science. Many of our staff began with the Project as student employees. The training, responsibility, autonomy, and respectable wages that we provide to students are rewarded by motivation, dedication, diligence, and fine work. We have employed and trained six students during this report period and we currently have two very effective student employees, among whose duties are processing our data archive and writing software.

Personnel Changes: Former student employees Andrew Tubbiolo, Mike Read, & Arianna Gleason became full time staff, in that sequence. Miwa Block was also hired as an observer and data analyst. Robert Jedicke accepted a tenure-track position in the PanSTARRS group at the Institute for Astronomy of the University of Hawaii, but he continues to collaborate with Spacewatch.

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